Comput. Methods Appl. Mech. Engrg. 268 (2014) 475–493

Contents lists available at ScienceDirect

Comput. Methods Appl. Mech. Engrg.

journal homepage: www.elsevier.com/locate/cma

Dynamic cloth simulation by isogeometric analysis

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ARTICLE INFO

Article history:
Received 1 May 2012
Received in revised form 18 September 2013
Accepted 24 September 2013
Available online 19 October 2013

Keywords:
Cloth simulation
Isogeometric analysis
Fabrics contact/impact
Draping
Virtual try-on

ABSTRACT

A NURBS-based continuum approach of cloth simulation is presented. Cloth geometry is described by NURBS, and the dynamic response is modeled by displacement-only NURBS shell. The shell formulation, including a constitutive description for cloth-like materials and an algorithmic treatment of multi-patch models, is discussed in detail. A fully NURBS based contact/impact update algorithm is presented. Numerical examples are included to demonstrate the performance and the application of the method.

1. Introduction

Cloth modeling finds applications in numerous technical fields, e.g. computer graphics, textile industry, garment design, and electronic commerce. While the mass-spring method continues to dominate in the computer graphics community [1–7], continuum models, which describe cloth by continuum mechanics theories, have attracted considerable attentions in the textile and apparel industrials. The spring-mass models are computationally efficient, but they are limited in their capability to accurately reproduce the mechanical behavior of fabric material. Studies [1,2] have attempted to determine spring parameters from experimental stress–strain and curvature-moment curves [8]. However, parameters so obtained are mesh dependent and thus not easily transferable across meshes of different topologies. In this regard, the continuum approach has the advantage that it admits standard constitutive descriptions which are independent of discretization through a wide range of mesh resolutions.

Many continuum schemes have been proposed in the literature. Collier et al. [9] developed a shell element with finite rotation and small strain to model draping process of cotton and achieved good agreement with experimental results. Gan et al. [10], Chen and Govindaraj [11], Eischen et al. [12] and Man and Swan [13] utilized degenerated continuum shell to simulate cloth. Kim [14] applied Simo's geometrically exact shell [15–17] to model cloth, and Deng et al. [18] developed a contact scheme based on Kim's work. Yu et al. [19] and Kang and Yu [20] described the cloth using plate element. In addition to shell and plate theories, Ascough et al. [21] modeled the cloth as a network of beams, and Teng et al. [22] used the finite-volume method. Together, these studies showed that, despite the coarse microstructure of fabric materials, continuum theories can effectively capture the characteristics of cloth deformation. However, the continuum simulations reported thus far are computationally expensive, and have limited contact/impact capabilities. The conventional displacement/force based contact algorithms are cumbersome for cloth simulation due to several reasons. For one, a piece of cloth can engage contact with an external body or itself on either side and can change the contact side over time, making it difficult to delineate the contact condition using a pre-set surface normal. Secondly, in the context of penalty method it is difficulty to select suitable penalty parameters. A higher penalty parameter, required by a proper enforcement of in-penetration constraint, often results

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0045-7825/$ - see front matter
http://dx.doi.org/10.1016/j.cma.2013.09.016

in an excessive perturbation to the motion and thus causes numerical problems. Because of these pitfalls, continuum simulations to date were mostly restricted to single piece models and simple contact conditions. By and large, there is a gap between the capability of continuum modeling and the demand of garment-level simulation of realistic cloth motion.

The goal of this work is to make a case for a continuum approach that can, or at least has the potential to, fill this gap. The proposed method follows the route of isogeometric analysis [23–26] wherein Computer Aided Design (CAD) geometry is directly utilized in analysis. In particular to this work, we use NURBS to describe geometry and model cloth dynamics using displacement-only NURBS shell [27,28]. An underlying premise is that the NURBS geometry, which possesses global smoothness, is more suited for describing wrinkles or folds that are the characteristics of cloth motion. We expect that NURBS can better capture smooth motions and do so with less number of degree-of-freedoms compared to finite element or mass-spring models. NURBS geometry also benefits contact treatments [29–32], enabling a smooth description of contact geometry and a patch-wise contact search. In a sense, the use of smooth geometry in cloth simulation is not novel. Thomaszewski et al. [33] proposed the use of subdivision shells [34,35]. B-splines and NURBS have been used in physical modeling of deformable bodies [36–38], including simulation of fabrics [36]. Yet, NURBS has an additional attribute, that it connects seamlessly with CAD. Nowadays CAD programs are routinely used in apparel design wherein garments are internally parameterized by NURBS. As is well known, NURBS entities has an intrinsic mesh, which can be refined or degree-elevated using geometric algorithms without changing geometry. For 2D NURBS objects, such mesh operations are straightforward and can be done internally, with minimal user interference. This presents a significant advantage for practical applications.

The present work is also concerned with contact/impact treatment in cloth simulation. Impact dynamics remains a challenging problem due to the nonlinear and non-smooth nature of the response. The difficulty is aggravated in cloth simulation because the contact conditions are generally much more complicated. As noted earlier, the conventional force/displacement based contact algorithms often find difficulties in cloth simulation. To deal with cloth contact/impact problems, many novel ideas were proposed. Since Moore et al. [39], many researchers, particularly Volino et al. [40,41] and Bridson et al. [6,7] and have embraced the idea of repulsive force which essentially smears the non-smooth contact interaction into a smooth function over a small (fictitious) contact distance. The concept is similar to the contact barrier method [42,43], whereby the on-and-off contact state characterized by an equality constraint is replaced by an inequality constraint to allow for a smooth transition between contact and non-contact states. Bridson et al. [6,7] combined the impulsive force concept with a safe-fail impact treatment to yield a robust updating algorithm, and integrated it into an explicit time-stepping scheme. Bridson'e method is essentially an operator-splitting scheme wherein the elastic restoring force and contact/impact actions were treated sequentially. In the presented work, this operator-splitting framework is adopted. We have introduced a fully NURBS-based contact update to exploit the advantage of geometric exactness.

The organization of this paper is as follows. The NURBS shell formulation, including a constitutive description for cloth-like materials and treatment of multi-patch model, is discussed in Section 2. Section 3 presents the contact/impact algorithm and integration method. Numerical examples are included in Section 4. The paper concludes in Section 5.

2. NURBS Kirchhoff–Love shell

We focus on *thin fabrics* that can be effectively described by Kirchhoff–Love shell theory. By thinness, one typically means that the thickness h is less that $1/20$ of the characteristic length in the lateral direction. The Kirchhoff–Love theory assumes that the transverse shear is negligible and thus the shell kinetics is described by in-plane stretching and lateral bending. In analysis, a Kirchhoff–Love element requires C^1 continuity between elements, which is difficult to achieve in Lagrangian- or Hermite-based finite element interpolations. NURBS geometry maintains a C^1 or higher order continuities by construction, and thus naturally supporting Kirchhoff–Love analysis [27]. The advantage of NURBS Kirchhoff–Love element, in comparison to the Reissner–Mindlin formulation in finite element geometry, e.g. [15,16], is that it is displacement-based; no rotational degree-of-freedoms are needed.

2.1. Kinematics

The NURBS formulation below follows Kiendl et al. [27]. We use the same set of NURBS basis functions $\{N_I\}$ to parameterize the reference and current configurations:

$$\begin{aligned} \mathbf{X} &= \sum_{I=1}^{n} N_I(\xi^1,\xi^2)\mathbf{Q}_I \\ \mathbf{x} &= \sum_{I=1}^{n} N_I(\xi^1,\xi^2)\mathbf{q}_I \end{aligned} \tag{1}$$

Here $\mathbf{Q}_I$'s are the reference coordinates of control points, and $\mathbf{q}_I$'s the current coordinates. (ξ^1, ξ^2) are knot parameters; in the sequel they serve as the convected coordinates whereby a pair of fixed values represents the same material point throughout the deformation. These two coordinates induce two convected surface basis vectors $\mathbf{a}_1 = \mathbf{x}_{,\xi^1}$, $\mathbf{a}_2 = \mathbf{x}_{,\xi^2}$ spanning the tangent plane at every point of the surface. A line element in the current configuration is thus represented as $d\mathbf{x} = \mathbf{a}_1 d\xi^1 + \mathbf{a}_2 d\xi^2$. In the reference configuration, the surface bases are denoted by $\{\mathbf{A}_1, \mathbf{A}_2\}$, and a line element is given by $d\mathbf{X} = \mathbf{A}_1 d\xi^1 + \mathbf{A}_2 d\xi^2$. The bases vectors are illustrated in Fig. 1.